IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Serial No.	:	**10/553972**
Applicant	:	Vasic et al.
Filing date	:	October 19, 2005
Title	:	Method and Device for the Authentication of Documents and Goods
TC/A.U.	:	2876
Examiner	:	**Brito Peguero**
Docket No.	:	**5734**
Customer No.	:	26936

Commissioner for Patents
P.O. Box 1450
Alexandria, Virginia 22313-1450

SUPPLEMENT TO RESPONSE

Sir:

Two documents referred to in the April 25 amendment were inadvertently not submitted with the amendment. Those documents are now attached.

Respectfully submitted,

/Charles Fallow/

Charles W. Fallow
Reg. No. 28,946

Shoemaker and Mattare, Ltd.
10 Post Office Road - Suite 100
Silver Spring, Maryland 20910
April 29, 2008

SPIE Milestone Series
Volume MS 106

Selected Papers on
Nonimaging Optics

Roland Winston, *Editor*
The University of Chicago
Department of Physics and
The Enrico Fermi Institute

Brian J. Thompson
General Editor, SPIE Milestone Series

SPIE OPTICAL ENGINEERING PRESS

A Publication of SPIE—The International Society for Optical Engineering
Bellingham, Washington USA

Library of Congress Cataloging-in Publication Data

Selected papers on nonimaging optics / Roland Winston, editor.
p. cm. — (SPIE milestone series ; v. MS 106)
Includes index.
ISBN 0-8194-1799-8.
1. Solar collectors. 2. Optics. I. Winston, Roland. III. Series.
TJ812.S45 1995 94-42849
621.36—dc20 CIP

ISBN 0-8194-1799-8

Published by
SPIE—The International Society for Optical Engineering
P.O. Box 10, Bellingham, Washington 98227-0010USA
Telephone 206/676-3290(Pacific Time) • Fax 206/647-1445

This book is a compilation of outstanding papers selected from the world literature on optical and optoelectronic science, engineering, and technology. SPIE Optical Engineering Press acknowledges with appreciation the authors and publishers who have given their permission to reprint material included in this volume. An earnest effort has been made to contact the copyright holders of all papers reproduced herein.

Printed in the United States of America

Selected Papers on

Nonimaging Optics

Contents

Reprinted from *Journal of the Optical Society of America,* Vol. 60(2), pp. 245-247 (February 1970).

Light Collection within the Framework of Geometrical Optics*

ROLAND WINSTON†
The Enrico Fermi Institute and Department of Physics, The University of Chicago, Chicago, Illinois 60637
(Received 28 June 1969)

The problem of light collection is examined from first principles within the framework of geometrical optics. From the outset, we distinguish between light collection and the usual theory of image formation. From phase-space considerations, we derive the sine inequality, a generalization of the Abbe sine law appropriate to nonimaging systems. We construct two- and three-dimensional nonimaging systems that reduce the f number to the least allowed by the sine inequality. Such systems give substantially improved light collection as compared with conventional systems.

INDEX HEADINGS: Geometrical optics; Ray tracing; Fiber optics.

The fundamental problem of light collection is: Given a set of light rays with a specified angular divergence θ_{max} distributed over an entrance aperture, how can we direct these rays efficiently onto the smallest possible exit aperture?

To solve this problem, it is essential to distinguish between light collection and imaging. In the usual theory of image formation, the well-known Abbe sine law provides the relation between image size, object size, and θ_{max}. For the purposes of light collection, however, imaging is not required; we can improve light collection by constructing nonimaging systems. In this paper we derive an appropriate generalization of Abbe's sine law and discuss solutions of light-collection problems based on this generalization.

THE SINE INEQUALITY

Inasmuch as it is intuitively obvious that phase-space considerations will be helpful in discussing the passage of trajectories (light rays) through a set of finite apertures, we adopt a hamiltonian description of our optical problem. Furthermore, we adopt a stationary, purely geometric formulation, and use one of the coordinates, say z, as the parameter that identifies the light rays. The alternative approach, in which time is used as a parameter, is less appropriate because, for nonimaging systems, rays that start simultaneously from z_1 (plane of the entrance aperture) will, in general, arrive at z_2 (the exit aperture) at different times.[1]

Let $x(z)$, $y(z)$ specify a light ray, and let these be single-valued functions of their argument z (this simply means that we exclude light rays that double back on themselves); a natural choice for z would be the distance along the optic axis. In terms of these functions, Fermat's principle can be written in the form

$$\delta\int_{z1}^{z2} n(1+\dot{x}^2+\dot{y}^2)^{\frac{1}{2}}dz=0, \tag{1}$$

where the dots denote differentiation with respect to z, and n is the index of refraction. We identify the integrand as the lagrangian of the light ray and derive the canonical momenta conjugate to x, y[2]

$$\begin{aligned} p_x &\equiv (\partial/\partial\dot{x})n(1+\dot{x}^2+\dot{y}^2)^{\frac{1}{2}}=n\dot{x}(1+\dot{x}^2+\dot{y}^2)^{-\frac{1}{2}} \\ p_y &\equiv (\partial/\partial\dot{y})n(1+\dot{x}^2+\dot{y}^2)^{\frac{1}{2}}=n\dot{y}(1+\dot{x}^2+\dot{y}^2)^{-\frac{1}{2}}. \end{aligned} \tag{2}$$

For meridional light rays propagating in the x–z plane, conservation of phase-space volume implies

$$\int_{z1} dxdp_x=\int_{z2} dxdp_x, \tag{3}$$

[1] Using time as the parameter of the light rays leads to the additional difficulty that the lagrangian vanishes identically. This is discussed by L. Landau and E. Lifshitz, *The Classical Theory of Fields* (Addison–Wesley Publishing Co., Inc., Cambridge, Mass., 1951), p. 139.

[2] The stationary description of light rays that we adopt is treated by R. K. Luneburg, *Mathematical Theory of Optics* (University of California Press, Berkeley, 1964).

* Research supported by the U. S. Atomic Energy Commission.
† Alfred P. Sloan Foundation fellow.

whereas for light rays in three dimensions,

$$\int_{z1} dxdydp_x dp_y = \int_{z2} dxdydp_x dp_y. \tag{4}$$

We are now in a position to generalize the Abbe sine law to nonimaging systems. Suppose that at every point of the entrance aperture (at z_1) light rays subtend all angles up to θ_{max} with respect to the z axis. From Eq. (3), we have

$$\int_{z1} dxdp_x = 2n_1 d_1 \sin\theta_{max}, \tag{5}$$

$$\int_{z2} dxdp_x \leq 2n_2 d_2, \tag{6}$$

so that

$$n_2 d_2 \geq n_1 d_1 \sin\theta_{max}, \tag{7}$$

where d_1, d_2 are the aperture widths at z_1, z_2 and the index of refraction is assumed constant over the entrance and exit apertures. Equation (7) is the sine inequality for meridional rays. To illustrate the content of Eq. (7), the entrance and exit phase space for a specific case is shown in Fig. 1. For propagation in three dimensions, we have, from Eq. (4),

$$\int_{z1} dxdydp_x dp_y = \Pi n_1^2 a_1 \sin^2\theta_{max}, \tag{8}$$

$$\int_{z2} dxdydp_x dp_y \leq \Pi n_2^2 a_2, \tag{9}$$

so that

$$n_2^2 a_2 \geq n_1^2 a_1 \sin^2\theta_{max}, \tag{10}$$

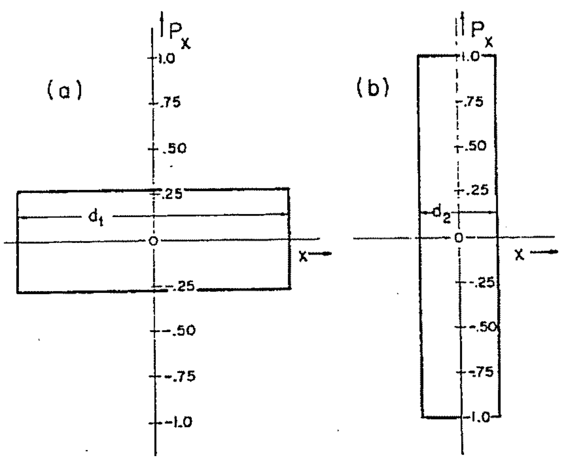


FIG. 1. (a) The area in phase space occupied by rays at the entrance aperture of a two-dimensional light collector. In this example, $\theta_{max} = 16°$, $n = 1$. (b) The area in phase space occupied by rays at the exit aperture of the same light collector. We have assumed $d_2 = d_1 \sin\theta_{max}$, the limiting case of Eq. (7).

where a_1, a_2 are the aperture areas at z_1, z_2 and the index of refraction is again assumed to be constant over the entrance and exit apertures. Equation (10) is the sine inequality for light rays propagating in three dimensions. For systems with rotational symmetry about z, for which the angular momentum $(xp_y - yp_x)$ is constant along a light ray, the equivalent of Eq. (10) can be derived simply.[3] For the ray with maximum angular momentum at z_1, we have

$$(xp_y - yp_x)_{z_1} = n_1 R_1 \sin\theta_{max}, \tag{11}$$

where R_1 is the radius of the entrance aperture. At the exit aperture we have for the same ray,

$$(xp_y - yp_x)_{z_2} \leq n_2 R_2, \tag{12}$$

where R_2 is the radius of the exit aperture, so that

$$n_2 R_2 \geq n_1 R_1 \sin\theta_{max}, \tag{13}$$

which is identical with Eq. (10) for rotationally symmetric systems.

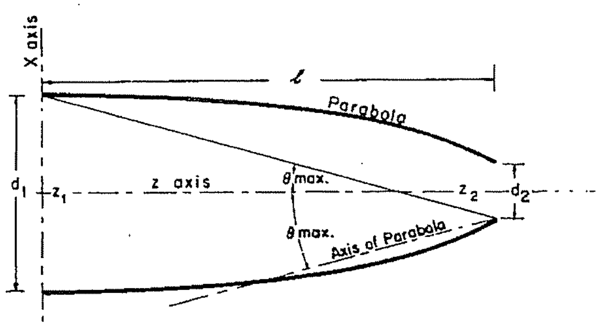


FIG. 2. Construction of an ideal light collector for the case of constant index of refraction. In this example, $\theta_{max} = 16°$.

Equations (7) and (10) provide the desired restriction on the exit aperture, imposed by the initial angular divergence, for optical systems that are not necessarily image forming.

IDEAL LIGHT COLLECTORS

We call an optical system that has the smallest f number allowed by the sine inequality an ideal light collector. As is well known from the theory of lenses, a system of lenses that acts as an ideal light collector would have an f number $= 0.5$, a physically unrealizable limit.[4] We are therefore led to consider the possibility of an ideal reflecting-surface collector.

The conservation of phase-space volume expressed by Eqs. (3) and (4) ensures that transmission of unwanted rays will necessarily result in reduced acceptance

[3] This result is derived by Luneburg,[2] also by J. Marshall, Phys. Rev. 86, 685 (1952).

[4] This follows from the connection between the f number and the Abbe sine law discussed in many optics texts. See, for example, M. Born and E. Wolf, *Principles of Optics* (Pergamon Press, Ltd., Oxford, 1965), 3rd ed.

for the rays of interest; hence, in order for a system to act as an ideal collector, it must reject all rays having $\theta > \theta_{max}$ at the entrance aperture. This complementary way of looking at the problem guides us to the solution. For simplicity we take up the case of meridional rays and constant index first.

A. Two-Dimensional Solution

As a necessary condition, we must exclude the possibility of direct rays with $\theta > \theta_{max}$ connecting entrance and exit aperture. The geometric construction shown in Fig. 2 shows that this implies a minimum length

$$l = z_2 - z_1 = (1/2)(d_1 + d_2) \cot\theta_{max}. \tag{14}$$

We now connect the two apertures by symmetric mirror curves that focus rays having $\theta = \theta_{max}$ onto the edge of the exit aperture, thereby rejecting rays having $\theta > \theta_{max}$ and hence collecting all of the light of interest. It is clear from elementary geometry that the required

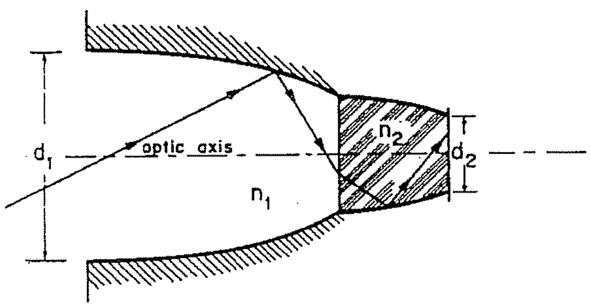


FIG. 3. Construction of an ideal light collector for the case $n_2 > n_1$. A typical light ray traversing the entire system is shown. In this example, $n_2/n_1 = 1.5$ and $\theta_{max} = 35°$ at the entrance aperture.

curves $x(z)$ are parabolas. This solution, which is unique for minimum l, has already been proposed.[5]

A case of practical importance ($n_2 > n_1$) is solved by two collectors of the above type in tandem, as shown in Fig. 3. The first of these, immersed in a medium of index n_1, is designed for θ_{max} appropriate to the angular divergence at the entrance aperture, whereas the second, immersed in a medium of index n_2, is designed for $\theta_{max} = \arcsin(n_1/n_2)$, the critical angle.[6] This solution minimizes the length of the second collector, which is often advantageous in practice.

B. Three-Dimensional Solution

The acceptance of skew rays by light collectors has been investigated in detail only for systems possessing

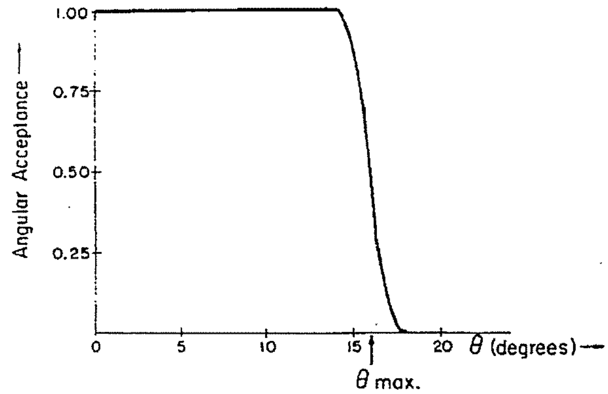


FIG. 4. The angular acceptance as a function of angle of incidence at the entrance aperture for an ideal three-dimensional light collector. Note that the angular acceptance cuts off over a region $\Delta\theta$ approximately 1° centered about θ_{max}. In this example, $\theta_{max} = 16°$.

axial symmetry.[7,8] For such systems, the similarity of the forms of Eqs. (7) and (13) suggests that if a solution is successful in the plane, the figure obtained by rotating the plane-profile curve about the optic axis should be satisfactory for skew rays. This is guaranteed for the skew rays with maximum angular momentum by Eq. (13) and for meridional rays by the two-dimensional solution. The behavior of intermediate cases is less obvious; we have examined the properties of the figures of revolution generated by the two-dimensional ideal solutions. We emphasize that whereas the plane-profile curve of such a surface is a parabola, the axis of the parabola is inclined at angle θ_{max} with respect to the optic axis, as shown in Fig. 2, so that the figure of revolution is not a paraboloid but a fourth-degree surface. We find by detailed ray tracing, using an IBM 7094 computer and a Monte Carlo technique, that the three-dimensional generalization indeed behaves in the ideal way by cutting off the angular acceptance at θ_{max}. However, when we examine the case more closely, we find that the cutoff takes place over a very narrow transition region $\Delta\theta$ centered about θ_{max} and not discontinuously as in the two-dimensional case. We find that $\Delta\theta$ is approximately 1°, nearly independent of θ_{max}. Figure 4 shows the angular acceptance in a typical case. Note that when the angle of incidence at the entrance aperture is exactly θ_{max}, the acceptance is approximately $\frac{1}{2}$. In practical applications, the distinction between a rigorously discontinuous and the quasi-discontinuous cutoff exhibited by the three-dimensional solution is academic because $\Delta\theta \ll \theta_{max}$.

ACKNOWLEDGMENTS

I would like to thank Professor V. L. Telegdi for his critical reading of the manuscript and Professor E. Zeitler for several helpful suggestions.

[5] H. Hinterberger and R. Winston, Rev. Sci. Instr. 37, 1094 (1966).

[6] H. Hinterberger and R. Winston, Rev. Sci. Instr. 39, 1217 (1968).

[7] D. E. Williamson, J. Opt. Soc. Am. 42, 712 (1952).

[8] W. Witte, Infrared Phys. 5, 179 (1965).

Reprinted from *Applied Optics*, Vol. 15(2), pp. 291-292 (February 1976).

Dielectric compound parabolic concentrators

Roland Winston

University of Chicago, Enrico Fermi Institute and Physics Department, Chicago, Illinois 60637.
Received 28 November 1975.
Sponsored by Jay M. Enoch, University of Florida.

The Compound Parabolic Concentrator (CPC) in both troughlike and conelike geometries has been described in previous papers.[1,2] Such devices can achieve a concentration ratio (entrance area/exit area)

$$x = n/\sin\theta_{\max} \text{ (trough)}, \tag{1}$$

$$x = n^2/\sin^2\theta_{\max} \text{ (cone)}, \tag{2}$$

where $\theta_{\max}$ is the angular acceptance (half-angle) and n is the index refraction of the collector relative to the surrounding medium. This concentration is the maximum permissable by physical principles.

The CPC is a nonimaging light funnel that derives its characteristic optical properties from the specific shape of the external wall, which is made specularly reflecting. The diameters of these structures are generally large relative to the wavelength of light. We have also investigated models of certain visual receptors, which strikingly resemble the compound parabolic shape and wherein the specularity was achieved by total internal reflection.[3,4] In these examples, chosen to simulate the conditions found in nature, a fraction of the light rays leaks out because they fail to satisfy the condition for total internal reflection.

The novel suggestion in this communication is the observation that for certain values of parameters (of considerable practical importance), the interface between the CPC and the surround becomes a perfect total internal reflection mirror that permits no leakage of radiation. This result is unexpected because the condition for maximal concentration [Eqs. (1) and (2)], which determines the shape of the external wall, and the condition for total internal reflection (angle of incidence exceeds the critical angle) have no *a priori* connection.

Incident rays that lie within the angular acceptance ($\theta_{\max}$) of the trough CPC are refracted into an elliptic cone of semiminor angle $\theta_{\max}'$ and semimajor angle θ_c, where

$$\sin\theta_{\max}' = (1/n)\sin\theta_{\max}, \text{ and} \tag{3}$$

$$\theta_c = \arcsin(1/n), \tag{4}$$

the critical angle. For the cone CPC the angular range is, to an excellent approximation, a cone of half-angle $\theta_{\max}'$.[5] These rays are funneled to the exit aperture after perhaps one or more reflections. For a ray to undergo total internal reflection at the wall, it must lie outside the critical cone of half-angle θ_c. For a trough CPC in contrast with a linearly tapered concentrator, rays within the acceptance angle

do not cross over from one side wall to the other. Therefore, the severest test of the total internal reflection condition occurs for the extreme meridional ray incident on the exit edge of the external wall (see Fig. 1). Then the condition becomes

$$\sin\theta_{max}' \leq (1 - 2/n^2), \tag{5}$$

so

$$\sin\theta_{max} \leq n(1 - 2/n^2), \tag{6}$$

$$x_{max} = 1/(1 - 2/n^2) \text{ (trough)}. \tag{7}$$

Notice that the onset of collection occurs at $n = \sqrt{2}$, but for $\sin\theta_{max} = 1$, Eq. (6) has the solution $n \geq 2$. Hence, the full range of angular acceptance $\pi/2 \geq \theta_{max} \geq 0$ is spanned by $2 \geq n \geq \sqrt{2}$, which is, in fact, a range of indices of refraction covered by common materials. Notice also that the end walls of a trough collector are total internal reflection mirrors for $n > \sqrt{2}$, which always holds after the onset of collection. For a case of practical importance, $n \approx 1.5$, we have $\theta_{max} \approx 10°$, $x_{max} \approx 9$. For solar energy collection applications, such a device requires no diurnal tracking but only occasional seasonal adjustment to follow the apparent motion of the sun.

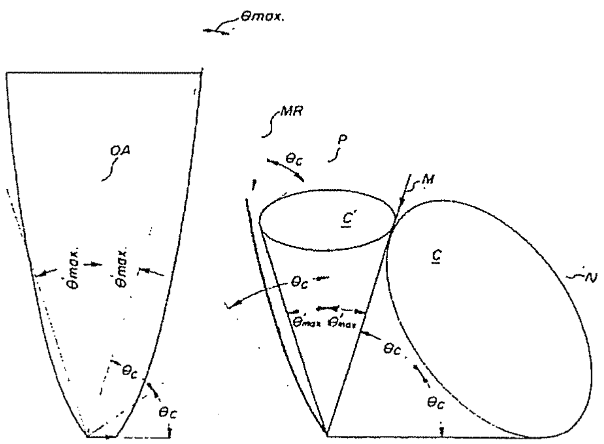


Fig. 1. The left half shows the profile curve of a compound parabolic concentrator (trough or cone). The optic axis is denoted by *OA*, and other quantities are defined in the text. The right half illustrates how the angular acceptance cone lies just outside the critical cone at the exit edge of the external wall and provides the basis for a geometric derivation of Eq. (5). The acceptance cone C' (axis P) is elliptic for a trough CPC and right circular for a cone CPC. The critical cone C (axis N) is tangent to the acceptance cone along the extreme meridional ray M. The ray MR illustrates that multiple reflections in a trough will be totally internally reflected.

For a cone CPC, the above argument applies directly to the meridional rays. Moreover, the fact that a maximum angle (θ_{max}) meridional ray impinging on any portion of the external wall always lies outside the critical cone ensures that all rays at the first and last reflection also lie outside the critical cone. This extends the argument up to and including two reflections. To check the behavior of skew rays undergoing more than two reflections (a small fraction of all accepted rays), a computer ray trace was performed. No failures of the condition for total internal reflection were found so we conclude that meeting the conditions of Eqs. (5) and (6) ensures that no rays leak out for the cone CPC as well. For the cone CPC the maximum concentration becomes

$$x_{max} = 1/(1 - 2/n^2)^2 \text{ (cone)}, \tag{8}$$

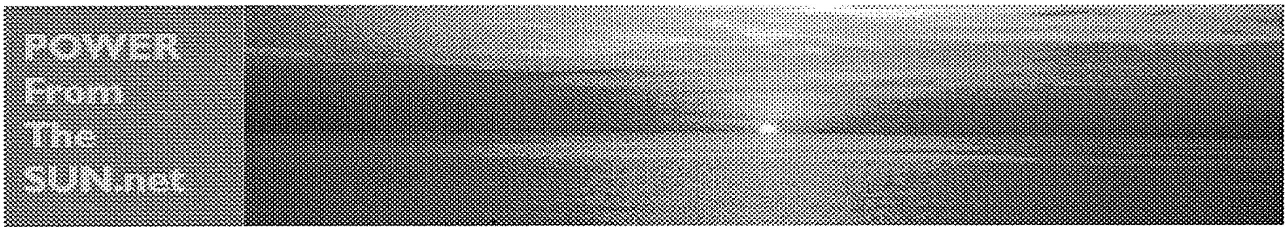
which assumes the value $x_{max} \approx 81$ for the example $n \approx 1.5$ used above.

Finally, we remark that the CPC design is generated by allowing the profile curve of the external wall to take on the maximum possible slope consistent with reflecting the extreme rays onto the receiver. Similarly, the dielectric CPC profile curve is generated by allowing the maximum possible slope consistent with *totally internally* reflecting the extreme rays onto the receiver. This guiding principle specifies the design for quite general combinations of angular acceptance, indices of refraction, and receiver shapes.

A more detailed publication describing various design concepts and performance analysis of the dielectric compound parabolic concentrator will be published jointly by the present author and N. S. Kapany in due course. The author is grateful to N. S. Kapany for stimulating an investigation of the concept of total internal reflection and how it might be applied to the CPC design. He is also grateful to M. F. Borun for helping to clarify the ideas presented in this note and to J. A. Simpson for support.

References

1. R. Winston, Sol. Energy 16, 89 (1974).
2. R. Winston, J. Opt. Soc. Am. 60, 245 (1970); this paper contains earlier references. See also V. K. Baranov and G. K. Melnikov, Sov. J. Opt. Technol. 33, 408 (1966).
3. R. Winston and J. M. Enoch, J. Opt. Soc. Am. 61, 1120 (1971).
4. R. Levi-Setti, D. A. Park, and R. Winston, Nature 253, 116 (1973).
5. D. A. Harper, R. H. Hildebrand, R. Stiening, and R. Winston, Appl. Opt. 15, 53 (1976).



home
Power from the Sun book
problem sets
■ ■ ■
sun angle calculator
solar time calculator
aperture irradiance calculator
system performance model
LEC calculator
■ ■ ■
J.T.Lyle Center for Regenerative Studies
other sites
contact us

Power From The Sun

Power From The Sun is the great new website by William Stine and Michael Geyer. It features a revised and updated (and free!) version of "*Solar Energy Systems Design*" by W.B.Stine and R.W.Harrigan (John Wiley and Sons, Inc. 1985) retitled "*Power From the Sun*", along with resources we hope you will find useful in learning about solar energy.

This website is meant to be a 'living' site where additions and changes are continuously being made. Currently the active tabs are:

- ***Power From The Sun - (most chapters)***
- ***Sun Angle Calculator***
- ***Solar Time Calculator***
- ***J.T.Lyle Center***
- ***contact us***

Press the buttons on the left and take a look!!!

Power From The Sun

by William B. Stine and Michael Geyer

News Flash! The Solar Angle Calculator, the Solar Time Calculator and the System Performance Model are now up and running...try them!

NOTE TO READER: Click on an equation and it will double in size for better readability!

Contents

Update News: We are constantly working to add material and make our site more useful. To this end, we have recently done the following:

- Corrected error in Equation 4.13. Thanks Scott McCreary (4/08)
- Corrected error in Equation 9.3 / S-B constant - Thanks Patrick Griffin (11/07)
- Added Chapter 15 System Design (5/07)
- Added Chapter 16 System Design Examples (5/07)
- Added Solar Time Calculator (5/07)
- Corrected error in Equation 10.7. Thanks Patrick Vielle, Switzerland (4/07)
- Added Solar Angle Calculator (2/07)
- Added Appendix G (4/06)
- Completed Chapter 11 Energy Storage (5/05)
- Completed Chapter 12 Power Cycles for Electricity Generation(10/04)
- Added Chapter 9 Concentrating Collectorsand Chapter 10 Central Receiver Systems (10/04) and corrected minor errors in Ch. 3 examples, in section 3.2 (thanks Sam Sankaran).
- Corrected error in Equation 3.10 (6/04) - Thanks Boudewijn van Leeuwen, The Netherlands
- Added Chapter 8 Concentrating Optics (10/03)
- We just added Chapter 6 describing flat-plate collectors (11/02)
- We have added Chapter 5 describing the performance and performance models of solar thermal and photovoltaic collectors (10/02).
- We have now added Chapters 3 and 4 covering all of the sun-collector angles necessary for solar calculations (8/02).
- Added Chapter 2 - The Sun's Energy This is an entirely updated version of Chapter 4 from Solar Energy Fundamentals and Design.
- Started (with Chapter 2 right now) incorporating MathType´s new web-based equation technology which is browser independent. It has the special features that you can double-click on an equation and it will increase in size, making the super and subscripts more legible. Also equation references in the text are hyperlinked to the equation and show in blue.

9. Concentrating Collectors

The optical principle of a reflecting parabola (as discussed in Chapter 8) is that all rays of light parallel to its axis are reflected to a point. A parabolic trough is simply a linear translation of a two-dimensional parabolic reflector where, as a result of the linear translation, the focal point becomes a line. These are often called line-focus concentrators. A parabolic dish (paraboloid), on the other hand, is formed by rotating the parabola about its axis; the focus remains a point and are often called point-focus concentrators.

If a receiver is mounted at the focus of a parabolic reflector, the reflected light will be absorbed and converted into heat (or directly into electricity as with a concentrating photovoltaic collector). These two principal functions, reflection to a point or a line, and subsequent absorption by a receiver, constitute the basic functions of a parabolic concentrating collector. The engineering task is to construct hardware that efficiently exploits these characteristics for the useful production of thermal or electrical energy. The resulting hardware is termed the *collector subsystem.* This chapter examines the basic optical and thermal considerations that influence receiver design and will emphasize thermal receivers rather than photovoltaic receivers.

Also discussed here is an interesting type of concentrator called a compound parabolic concentrator (CPC). This is a non-imaging concentrator that concentrates light rays that are not necessarily parallel nor aligned with the axis of the concentrator.

- To complete this section we describe engineering prototype concentrators that have been constructed and tested. Parabolic concentrators that are not commercial products were chosen for discussion. This allows free discussion without concern for revealing proprietary information. In addition, the prototype concentrators discussed are representative of the parabolic concentrators under development for commercial use, and considerable design information is available.

Performance data from some early prototypes are presented. The development includes the following topics:

- Receiver Design
    - Receiver Size
    - Receiver Heat Loss
    - Receiver Size Optimization
- Compound Parabolic Concentrators (CPC)
- Prototype Parabolic Troughs
    - Sandia Performance Prototype Trough
- Prototype Parabolic Dishes
    - Shenandoah Dish
    - JPL PDC1
- Other Concentrator Concepts
    - Fixed-Mirror Solar Collector (FMSC)
    - Moving Reflector Stationary Receiver (SLATS)
    - Fixed-Mirror Distributed Focus (FMDF) (spherical bowl)
- Prototype Performance Comparisons

9.2 Compound Parabolic Concentrators (CPC)

CPC Design Concepts - An interesting design for a concentrating collector makes use of the fact that when the rim of a parabola is tilted toward the sun, the rays are no longer concentrated to a point, but are all reflected somewhere below the focus. The rays striking the half of the parabola which is now tilted away from the sun are reflected somewhere above the focus. This can be seen on Figure 8.10 (repeated below as Figure 9.9) where the rays on the right-hand side are reflecting below the focus and the rays on the left-hand side are reflecting above the focus. If the half parabola tilted away from the sun is discarded, and replaced with a similarly shaped parabola with its rim pointed toward the sun, we have a concentrator that reflects (i.e. traps) all incoming rays to a region below the focal point.

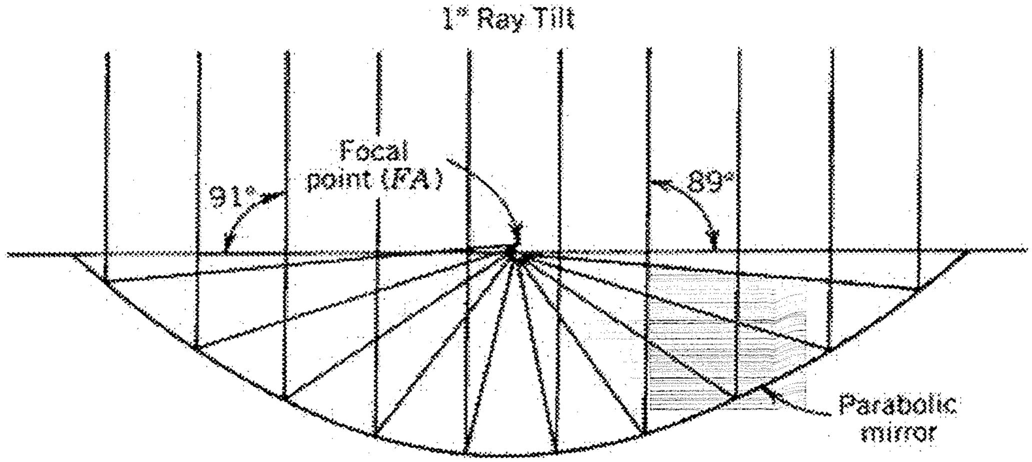


Figure 9.9 Off-axis light reflection from parabolic mirror.

Since the rays are no longer concentrated to a single point, this design is called a *non-imaging concentrator.* A receiver is now placed in the region below the focus and we have a concentrator that will ′trap′ sun rays coming from any angle between the focal line of the two parabola segments. Receivers can be flat plates at the base of the intersection of the two parabola, or a cylindrical tube passing through the region below the focus.

The basic shape of the compound parabolic concentrator (CPC) is illustrated in Figure 9.10. The name, compound parabolic concentrator, derives from the fact that the CPC is comprised of two parabolic mirror segments with different focal points as indicated. The focal point for parabola *A* (F_A) lies on parabola *B*, whereas the focal point of parabola *B* *(FB)* lies on parabola *A*. The two parabolic surfaces are symmetrical with respect to reflection through the axis of the CPC.

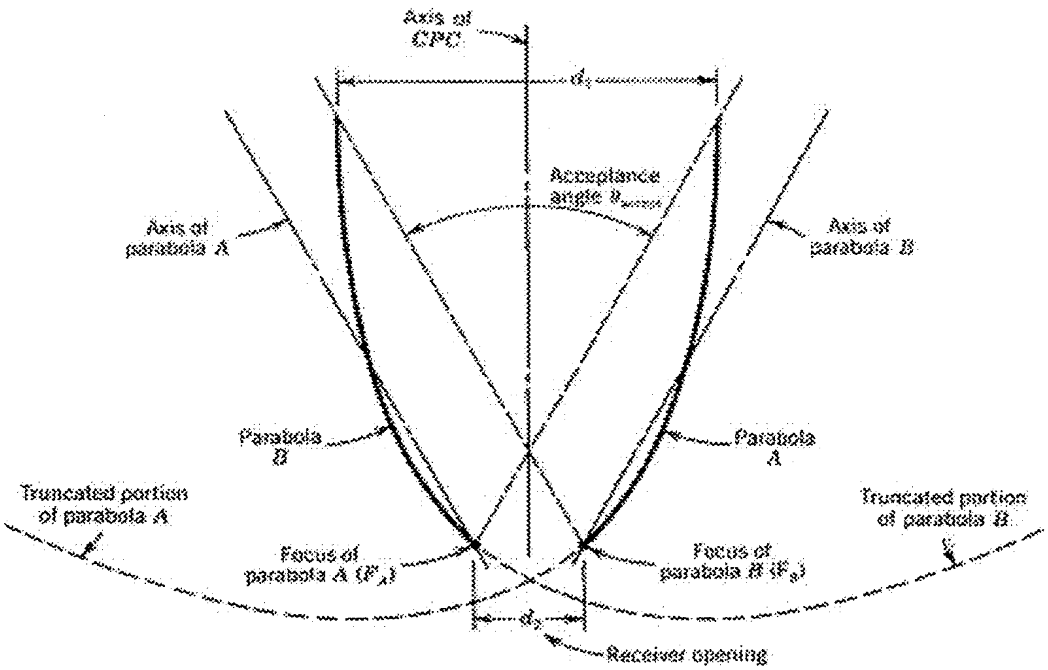


Figure 9.10 The compound parabolic concentrator (CPC).

The axis of parabola *A* is also shown in Figure 9.10 and, by definition, passes through the focal point of parabola *A* and the axis of parabola *B* likewise passes through the focal point of parabola *B*. The angle that the axes of the parabola *A* and *B* make with axis of the CPC defines the *acceptance angle* of the CPC. Light with an incidence angle less than one-half the acceptance angle will be reflected through the receiver opening (see Figure 9.11a). Light with an incidence angle greater than one-half the acceptance angle will not be reflected to the receiver opening (Figure 9.11b) and will, in fact, eventually be reflected back out through the aperture of the CPC.

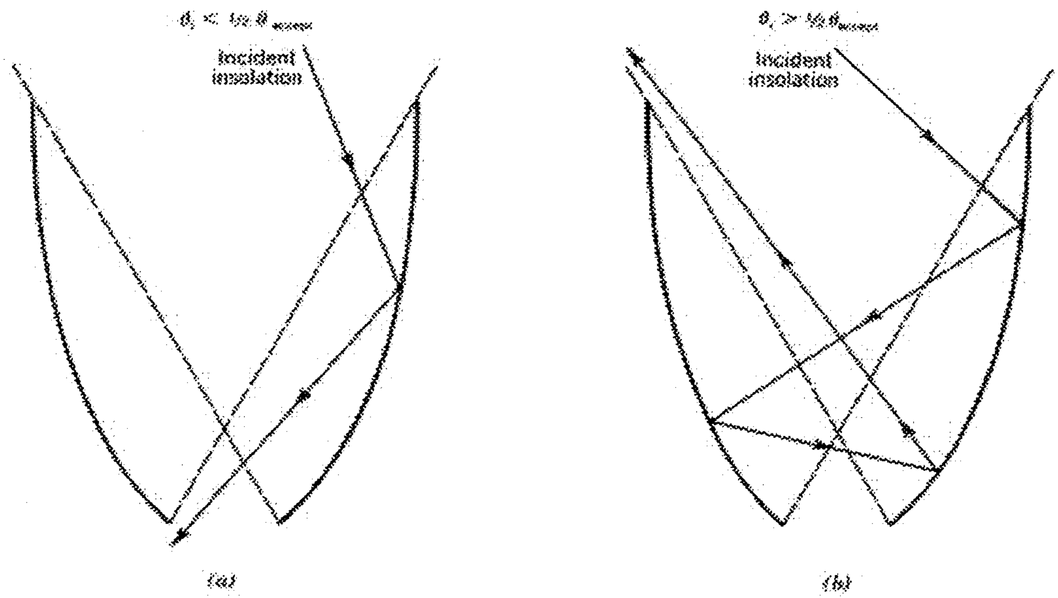


Figure 9.11 Light reflection from the CPC. a) Incidence angle less than acceptance angle; b) Incidence angle greater than acceptance angle.

The concentrating ability of the CPC can be understood through the use of ray tracing diagrams. The off-axis optics of parabolic troughs were discussed briefly in Chapter 8. That discussion is expanded here in order to explain the concentrating ability of the CPC.

If beam solar irradiance parallel to the axis of parabola *A* were incident on the CPC shown in Figure 9.10, the light would be perfectly focused (ignoring the 0.5 degree solar degree-width and any mirror inaccuracies) to point *FA*, the focal point of parabola *A*. The behavior of beam solar irradiance not parallel to the axis of parabola *A* is shown in Figure 9.9. Note that all of the solar irradiance incident on the right half of the parabola is reflected such that it passes beneath the focal point between the focal point and the surface of the parabolic mirror.

If the right half of the parabola in Figure 9.9 is tilted up to angle one-half the acceptance angle in order to approximate the orientation of parabola A in Figure 9.10, the situation would be analogous to that depicted in Figure 9.11a. All incident beam solar irradiance that is inclined to the right of the axis of the parabola in Figure 9.9 would he reflected by the right hand segment of the parabola beneath the focal point. Thus such solar irradiance would enter the receiver opening of an equivalent CPC.

The converse situation is true where the angle of incidence is greater than one-half the acceptance angle. This situation is represented by the left half of the parabola in Figure 9.9.

In this situation, all the incident beam solar irradiance is reflected above the focal point of the parabola and would not, as indicated in Figure 9.11*b*, enter the receiver opening of an equivalent CPC.

In operation, the CPC is usually deployed with its linear receiver aligned along an E/W line. The aperture of the CPC is typically tilted toward the south so that the incident solar irradiance enters within the acceptance angle of the CPC. Provided the sun's apparent motion does not result in the incident solar irradiance falling outside the CPC's acceptance angle, the CPC's aperture need not be tracked. Typically, a CPC's aperture need not be tracked on an hourly basis throughout a day since the sun's declination does not change more than the acceptance angle throughout a day. However, the tilt of the CPC may have to be adjusted periodically throughout the year if the incident solar irradiance moves outside the acceptance angle of the CPC.

The geometric concentration ratio of a CPC is related to the acceptance angle by

$$CR_g = \frac{1}{\sin\left(\frac{1}{2}\theta_{accept}\right)} \tag{9.7}$$

where θ_{accept} is the acceptance angle of the CPC.

As the concentration ratio of the CPC is increased in an attempt to increase performance at elevated temperatures, the acceptance angle of the CPC must be reduced. The narrowing of the acceptance angle results in a requirement for increasing the number of tilt adjustments of the CPC throughout the year. Table 10.1 lists the number of tilt adjustments needed for CPC collectors with various concentration ratios. Cosine effect changes due to these adjustments are not included on this table.

Table 10.1. Tilt Requirements of CPCs with Different Acceptance Angles (Rabl, 1980)

Acceptance Half-Angle	Collection Time Average over Year (h/day)	Number of Adjustments per Year	Shortest Period Without Adjustment (days)	Average Collection Time if Tilt Adjusted Every Day (h/day)
19.5°	9.22	2	180	10.72
14°	8.76	4	35	10.04
11°	8.60	6	35	9.52
9°	8.38	10	24	9.08
8°	8.22	14	16	8.82
7°	8.04	20	13	8.54
6.5°	7.96	26	9	8.36
6°	7.78	80	1	8.18
5.5°	7.60	84	1	8.00

Prototype Performance - The performance of the Concentrating Parabolic Concentrator (CPC) varies with the acceptance angle. An acceptance angle of 180 degrees is equivalent to a flat-plate collector, and an acceptance angle of 0 degrees is equivalent to a parabolic concentrator.

There has not been extensive performance testing of the CPC concept. As a result, there is to the authors' knowledge no published *ΔT/I* curve for CPCs. However, the Solar Energy Research Institute (Anonymous, 1979) has used the equation

$$\eta_{col} = 0.73 - 0.64\left(\frac{T_r - T_a}{I_a}\right) \qquad (9.8)$$

where the variables are defined as in Chapter 5. This equation is for a CPC with a concentration ratio of 5, resulting in an acceptance angle of about 19 degrees. Sharp (1979) has evaluated this equation and found it to be equivalent to that of a good parabolic trough. However, Sharp has pointed out that parasitic losses associated with pumping the heat-transfer fluid through the small tubing typically used in CPC receivers could be a major problem. Unfortunately, there is, as stated previously, a general lack of published test data.

It might be pointed out that computation of the CPC thermal energy production with the use of Equation (9.8) is straightforward if one assumes that the CPC tracks the sun about one axis. This is essentially what results from the multiple tilt adjustments given in Table 10.1. Since there is a general lack of data on the angular dependence of diffuse solar irradiance about the beam solar irradiance, Sharp (1979) suggests use of the beam solar irradiance in

computing CPC performance in clear climates even though a fraction of the diffuse solar irradiance is captured. If data were available, the diffuse solar irradiance falling within the CPC's acceptance could be included in Equation (9.8).